

APPLICATION FOR UNITED STATES PATENT

COMPLEX MULTIPLE FEEDBACK FILTER

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COMPLEX MULTIPLE FEEDBACK FILTER

FIELD OF THE INVENTION

5 The present invention relates generally to a filter. An image rejection filter with two poles per op amp is disclosed.

BACKGROUND OF THE INVENTION

10 There is a need for better image rejection filters to be used in wireless systems. In general, an image rejection filter is implemented as a bandpass filter that passes only positive frequencies. Since the magnitude of the transfer function is not symmetric about DC, the transfer function is complex. Figure 1 is a diagram illustrating a low pass to bandpass filter transformation. Since the filter shown requires complex signals, it needs to be implemented as a filter with two real inputs. Figure 2 is a block diagram illustrating an implementation of such a complex filter. Input 202 is referred to as the in phase or I input and input 204 is referred to as the quadrature or Q input. As shown in Figure 2, the I channel and the Q channels are linked. An output QO of the Q channel 214 is fed into a second input I2 to the I channel 206. Likewise, an output IO of the I channel 212 is fed into a second input Q2 to the Q channel 208.

15 Ideally, to implement a complex filter as shown in figure 2 it would be useful to have a filter that has a minimum number of op amps or other active components.

20 "CMOS Mixers and Polyphase Filters for Large Image Rejection" by Farbod Behbahani, Yoji Kishigami, John Leete, and Asad A. Abidi, published in the IEEE Journal of Solid-State Circuits, Vol. 36, No. 6, June 2001, page 873 and 878 describes a polyphase multiple pole filter that includes several RC stages. The design is useful, but it is difficult to implement desired types of bandpass filters and the multiple stages attenuate the signal

so that amplification of the output is required. "An Image-Rejecting Mixer and Vector Filter with 55-dB Image Rejection over Process, Temperature, and Transistor Mismatch," Thomas Hornak, Knud L. Knudsen, Anderew Z. Grezegorek, Ken A. Nishimura, and William J. McFarland, IEEE Journal of Solid-State Circuits, Vol. 36, No. 1, January

5 2001, page 23 and 26 describes an image rejection filter that integrates op amps into the filter design so that amplification is built into the filter. This design also has the advantage that desired types of bandpass filter responses can be implemented. However, the illustrated design only provides one pole per op amp. A complex multiple pole filter therefore would require an op amp for each pole in each channel. It would be desirable if
10 a filter could be designed that could be used in an image rejection system and would use fewer op amps per pole. Such a filter could use less power and take up less space on a chip than currently available designs.

SUMMARY OF THE INVENTION

A complex multiple feedback filter is disclosed. A multiple feedback filter that realizes two poles and a single op amp is implemented in the I and Q channels. A first linking network of capacitors and resistors links a Q channel output back to an I channel input and a second linking network of capacitors and resistors links an I channel output back to a Q channel input. In this manner, a complex filter is implemented with two poles and only one op amp in the I channel and one op amp in the Q channel. Higher order complex filters can be implemented by cascading the two pole filter design.

It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system, a device, a method, or a computer readable medium such as a computer readable storage medium or a computer network wherein program instructions are sent over optical or electronic communication links. Several inventive embodiments of the present invention are described below.

In one embodiment, a complex filter includes an I channel having a first I channel output and a second I channel output and a Q channel having a first Q channel output and a second Q channel output. The second I channel output is input to the Q channel through a first passive network and wherein the second Q channel output is input to the I channel through a second passive network.

These and other features and advantages of the present invention will be presented in more detail in the following detailed description and the accompanying figures which illustrate by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings, wherein like reference numerals designate like structural elements, and in which:

5 Figure 1 is a diagram illustrating a low pass to bandpass filter transformation.

Figure 2 is a block diagram illustrating an implementation of such a complex filter.

Figure 3 is a block diagram illustrating a multiple feedback filter 300 with a second order transfer function having 2 poles and a single op amp.

10 Figure 4 is a block diagram illustrating a filter.

Figure 5 is a block diagram illustrating a filter.

Figure 6 is a diagram illustrating a desired filter configuration.

Figure 7 is a diagram illustrating a passive network.

Figure 8 is a diagram illustrating a network.

15 Figure 9 is a diagram illustrating a network.

Figure 10 is a block diagram illustrating two second order filters each implemented using a single op amp.

DETAILED DESCRIPTION

A detailed description of a preferred embodiment of the invention is provided below. While the invention is described in conjunction with that preferred embodiment, it should be understood that the invention is not limited to any one embodiment. On the contrary, the scope of the invention is limited only by the appended claims and the invention encompasses numerous alternatives, modifications and equivalents. For the purpose of example, numerous specific details are set forth in the following description in order to provide a thorough understanding of the present invention. The present invention may be practiced according to the claims without some or all of these specific details. For the purpose of clarity, technical material that is known in the technical fields related to the invention has not been described in detail so that the present invention is not unnecessarily obscured.

Figure 3 is a block diagram illustrating a multiple feedback filter 300 with a second order transfer function having 2 poles and a single op amp.

The design equations can be derived as follows:

KCL at node A:

$$\frac{(v_i - v_{C1})}{R_1} - sC_1v_{C1} + \frac{(v_o - v_{C1})}{R_2} - \frac{v_{C1}}{R_3} = 0 \quad (1)$$

After rearrangement:

$$\frac{v_i}{R_1} = -\frac{v_o}{R_2} + v_{C1} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right) \quad (2)$$

KCL at Node B:

$$\frac{v_{C1}}{R_3} + sC_2v_o = 0 \Rightarrow v_{C1} = -v_o sR_3C_2 \quad (3)$$

Substituting (3) in (2):

$$\frac{v_i}{R_1} = -v_o \left[sR_3C_2 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right) + \frac{1}{R_2} \right] \quad (4)$$

$$\frac{v_o}{v_i}(s) = \frac{H_0 \omega_0^2}{s^2 + \frac{\omega_0}{Q} s + \omega_0^2} \quad (5)$$

$$= \frac{-\frac{R_2}{R_1} \frac{1}{C_1 C_2 R_2 R_3}}{s^2 + \frac{1}{C_1} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) s + \frac{1}{C_1 C_2 R_2 R_3}} \quad (6)$$

By inspection:

$$H_0 = -\frac{R_2}{R_1} \quad (7)$$

$$\omega_0^2 = \frac{1}{C_1 C_2 R_2 R_3} \quad (8)$$

$$\frac{\omega_0}{Q} = \frac{1}{C_1} \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) \quad (9)$$

As can be seen from equation (6), multiple feedback filter 300 has a second order transfer function as desired. To implement an arrangement as shown in Figure 2, filter 300 is configured to receive two inputs and to have an output that drives a filter in another channel. In one embodiment, one second order filter per channel each having a single op amp is implemented using the configuration derived below.

If the original transfer function is $H(j\omega)$, the complex band-pass transfer function is $H(j\omega')$ where $\omega' = \omega - \omega_c$. Since the only frequency dependent components of the filter shown in Figure 1 are capacitors, the complex filter can be obtained from the circuit by transforming each capacitor to a composite device as shown in Figure 4.

The resulting filter would look like Figure 5 with:

$$i_1 = -j\omega_c C_1 v_A \quad (10)$$

$$i_2 = -j\omega_c C_2 v_o \quad (11)$$

Consider two such filters H_R and H_I such that H_R is excited with the input signal v_i and H_I is excited by jv_i . Denote the nodes voltages of the corresponding filter with v_A^* and v_o^* . In other words:

$$i_1 = -\omega_c C_1 v_A^* \quad (12)$$

$$i_2 = -\omega_c C_2 v_o^* \quad (13)$$

The controlled current source in Figure 5 subtracts current from node A and depends on the voltage v_A^* with the coefficient $-\omega_c C_1$. This current source cannot be implemented with passive components because adding passive components to node A changes the transfer function. Furthermore the current depends on the voltage of the corresponding node, A^* , in the complex filter. However, nodes A and A^* are not low impedance nodes; therefore, they cannot drive impedances without buffers.

In general, it is desired that the driving point for the outputs to the other channel is at the op amp output so that there is low impedance. Also, it is desired that the mixing point at the input is at the op amp input where there is a virtual ground.

A suitable implementation can be obtained first using v_o^* as the controlling voltage rather than v_A^* :

$$i_1 = -\omega_c C_1 v_A^* \quad (14)$$

$$= -\omega_c C_1 \frac{v_A}{v_o} v_o^* \quad (\text{Note: } \frac{v_A}{v_o} = \frac{v_A^*}{v_o^*}) \quad (15)$$

The transfer function v_A/v_o can be found by inspection:

$$\frac{v_A}{v_o} = -R_3 C_2 (s - j\omega_c) \quad (16)$$

The next step is to use the op-amp input as the current summing junction. With this change, passive components between the op-amp inputs and outputs of the complex filters can be used for the cross-coupling elements. Figure 6 is a diagram illustrating the desired configuration. The controlled current source i_2 can be moved to between op-amp input and ground without changing the transfer function. Replacing i_1 with i_x should produce the same output voltage v_o . KCL at node A in Figure 5:

$$\frac{v_A}{R_1} + sC_1 + \frac{v_A}{R_3} + \frac{v_A - v_o}{R_2} + i_1 = 0 \quad (17)$$

$$v_A \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right) = \frac{v_o}{R_2} - i_1 \quad (18)$$

Using (16):

$$-v_o R_3 C_2 (s - j\omega_c) \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right) = \frac{v_o}{R_2} - i_1 \quad (19)$$

Finally,

$$v_o = i_1 \frac{1}{R_3 C_2 (s - j\omega_c) \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right) + \frac{1}{R_2}} \quad (20)$$

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The output, v_o in Figure 6 can be found similarly. KCL at node A:

$$v_A \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right) = \frac{v_o}{R_2} \quad (21)$$

KCL at node B:

$$\frac{v_A}{R_3} + i_x + v_o C_2 (s - j\omega_c) = 0 \quad (22)$$

$$v_A = -i_x R_3 - v_o R_3 C_2 (s - j\omega_c) \quad (23)$$

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Substituting (23) in (21):

$$\frac{v_o}{R_2} = -v_o R_3 C_2 (s - j\omega_c) \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right) - i_x R_3 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right) \quad (24)$$

$$v_o = \frac{-i_x R_3 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right)}{R_3 C_2 (s - j\omega_c) \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right) + \frac{1}{R_2}} \quad (25)$$

Equating (20) and (25):

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$$i_x = \frac{-i_1}{R_3 \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + sC_1 \right)} \quad (26)$$

$$= \frac{-i_1}{R_3 C_1} \left(\frac{1}{s + \frac{\omega_0}{Q}} \right) \quad (27)$$

Using (27), (16), and (15):

$$i_x = -\omega_c C_1 [-R_3 C_2 (s - j\omega_c)] \frac{-1}{R_3 C_1 \left(s + \frac{\omega_0}{Q} \right)} v_o^* \quad (28)$$

$$= -\frac{\omega_c C_2 (s - j\omega_c)}{s + \frac{\omega_0}{Q}} v_o^* \quad (29)$$

$$= -\frac{\omega_c s C_2}{s + \frac{\omega_0}{Q}} v_o^* - \frac{\omega_c^2 C_2}{s + \frac{\omega_0}{Q}} v_o \quad (\text{Note: } jv_o^* = -v_o) \quad (30)$$

5 Each term in (30) describes an admittance function. The first term has the form:

$$i = K \frac{s}{s + p} v \quad (31)$$

Consider the passive network in Figure 7.

$$i = \frac{1}{R_x} \frac{s}{s + \frac{1}{R_x C_x}} v \quad (32)$$

Comparing terms:

$$R_x = \frac{1}{\omega_c C_2} \quad (33)$$

$$C_x = \frac{1}{R_x \frac{\omega_0}{Q}} \quad (34)$$

$$= \frac{\omega_c C_2}{\frac{\omega_0}{Q}} \quad (35)$$

The second term in (30) has the form:

$$i = K \frac{1}{s + p} v \quad (36)$$

15 The natural choice is an $R - L$ series network as in Figure 8

$$i = \frac{1}{R_y + sL_y} v \quad (37)$$

$$= \frac{1}{L_y} \frac{1}{s + \frac{R_y}{L_y}} \quad (38)$$

Although the form of the transfer function is correct, the inductor is not suitable for IC implementation.

Consider the "T" network in Figure 9

$$i = \frac{1}{R_y^2 C_y} \frac{1}{s + \frac{2}{R_y C_y}} v \quad (39)$$

Comparing terms:

$$R_y = \frac{1}{2\omega_c^2 C_2} \frac{\omega_0}{Q} \quad (40)$$

$$C_y = \frac{2}{R_y} \frac{1}{\frac{\omega_0}{Q}} \quad (41)$$

$$= 4\omega_c^2 C_2 \left(\frac{\omega_0}{Q} \right)^2 \quad (42)$$

Figure 10 is a block diagram illustrating two second order filters (one for each channel) each implemented using a single op amp. Resistor $R_z = 1/\omega_c$ C_2 implements the

controlled current source i_2 . Second order filter 1002 is implemented in the I channel and Second order filter 1012 is implemented in the Q channel. In the embodiment shown, inverting buffers 1003 and 1013 provide inverted outputs. In a fully differential implementation, both polarities of the output are available; therefore, the inverting buffers are not needed. Passive network 1004 enables an output IO from the I channel to be fed into input Q2 of the Q channel. Likewise, passive network 1014 enables an output QO from the Q channel to be fed into an input I2 of the I channel. It should be noted that the coupling network shown in Figure 10 is exemplary and in other embodiments, other coupling networks are used.

A complex multiple feedback filter has been described. A multiple feedback filter that includes two poles and a single op amp is implemented in the I and Q channels. A first linking network of capacitors and resistors links a Q channel output back to an I channel input and a second linking network of capacitors and resistors links an I channel output back to a Q channel input. In this manner, a complex filter is implemented with two poles and only one op amp in the I channel and one op amp in the Q channel.

Although the foregoing invention has been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. It should be noted that there are many alternative ways of implementing both the process and apparatus of the present invention. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein, but may be modified within the scope and equivalents of the appended claims.

WHAT IS CLAIMED IS:

1. A method of determining a value of a function of a variable, the method comprising: receiving a value of the variable; and determining the value of the function of the variable based on the received value of the variable.